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IMPLICATIONS OF SUBMERGENCE FOR COASTAL ENGINEERS.(U)
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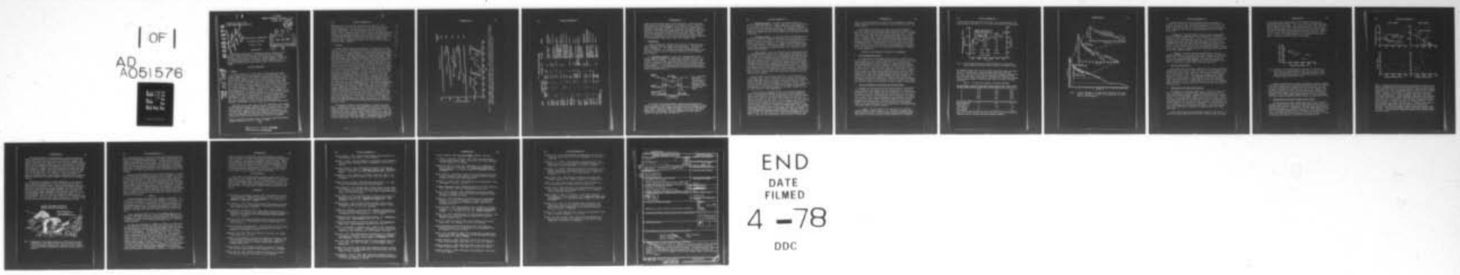

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IMPLICATIONS OF SUBMERGENCE FOR COASTAL ENGINEERS

Edward B. Hands[1]

INTRODUCTION

Submergence affects most US shorelines, and has created serious problems in many localities by increasing flooding, accelerating erosion, altering surface drainage, and causing structural damage. The purpose of this paper is to present selected examples illustrating the problems engineers face in areas of coastal submergence and to discuss in general how sea-level changes affect long term shore processes.

COASTAL SUBMERGENCE

1. Causes.

Eustatic changes in sea level refer to ocean wide events which reflect changes in either the capacity of the ocean basins, or the volume of ocean waters. Many authors, beginning with Gutenberg (1941), have published estimates of the rate of recent eustatic rise in sea level. Most of these estimates are based on averaging linear trends fit to tide curves. The tidal stations are selected throughout the world in an effort to minimize regional or local effects. The decision as to which stations to include varies from author to author, and so too, do the resulting estimates. Because there is no adequate world wide reference surface, an exact description of eustatic change remains undetermined. For present purposes, it is useful simply to point out that authorities do agree the present century has been a period of rising sea level in the mid-latitudes of the northern hemisphere. Approximately 1 mm/yr is judged to be an acceptable nominal rate for this rise. Lisitzin (1974) provides an outstanding review of world wide sea level studies. Harris (in prep) provides guidance to engineers on measuring sea level changes and determining tidal datums.

Additional factors which affect sea level measurements are regional *land movement* and regional temporary *bulges in the water column*. These factors introduce irregularities which are superimposed on the *eustatic* rise and produce regional effects of submergence and emergence. On the world scale, emergence most often prevails in formerly glaciated areas, and submergence is pronounced in areas marginal to formerly depressed areas, and from which sub-crustal material is presumably

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migrating back to the formerly glaciated areas (Walcott, 1972). Most permanent tide stations within the US indicate trends towards coastal submergence. The only exceptions are Cresent City, CA; Astoria, OR; Neah Bay, WA; and the Alaska stations (National Ocean Survey, 1972). Anomalously high rates of coastal *submergence* are being caused by regional land subsidence in the vicinities of the Delaware and Chesapeake embayments, along central Florida's Atlantic shore, and in several areas of the Texas/Louisiana Gulf Coast, (Holdahl and Morrison, 1974). Examples of relative rise in sea level at selected sites are shown in Figure 1.

2. Examples

Though coastal engineers are usually not concerned with secular trends in sea level, in specific localities the relative rise in sea level has been of crucial importance in planning and designing engineering projects. In Long Beach Harbor, CA, where man-induced subsidence affected 52 km^2 of federal, municipal, and industrial property, damage and alleviation costs reached an estimated $100 million before subsidence was brought under control (references to this and following case histories are indicated in Table 1). Although active subsidence of the San Joaquin Valley (CA) doesn't affect coastal property, it is of interest, not only as having the largest magnitude and being the most extensive area of man-induced subsidence in the world but also because it is (as a result of the gigantic engineering effort that has gone into the California Aqueduct System) the best documented and best understood case of induced subsidence. Houston, Bay Town, Texas City, and Galveston, TX, and New Orleans, LA are among some of the US coastal cities with recognized subsidence problems. On a world scale the flooding due to subsidence of Venice, Italy is perhaps best known. In Venezuela subsidence related to oil production necessitated the construction of 44 km of coastal dikes to protect the eastern shore of Lake Maracaibo. On a much longer time scale, the Pleistocene glaciation which depressed the Scandinavian crust, also caused a compensating upward bulge in the area of the Netherlands. Return to equilibrium is still taking place (Meinesz, 1954). According to Bruun (1973) and Thijsse (1958) land elevations in the Netherlands were still high enough 2000 years ago for habitation with no concern for coastal protection. About 1000 years ago, the Dutch began to build earth mounds to which they could retreat during storm tides. Subsidence has continued and the success of the Dutch in reclaiming and defending land from the encroaching sea, is well known. A collection of eighteen papers discussing subsidence, sea level fluctuations, and coastal protection was published by the Royal Netherlands Geological and Mining Society in 1954.

The foregoing examples concerned gradually accumulating submergence. Submergence can also result suddenly from tectonic activity. During the March 1964 Alaskan earthquake, the shorelines of Kenai Peninsula, Kodiak Island, and Cook Inlet subsided several feet. Over the following three years, beaches receded, frontal dunes were eroded, and coastal bluffs were undermined. Climatic and meterological variations, as well as man's activities, contribute to submergence along lake and reservoir shorelines. The Great Lakes provide prime examples of

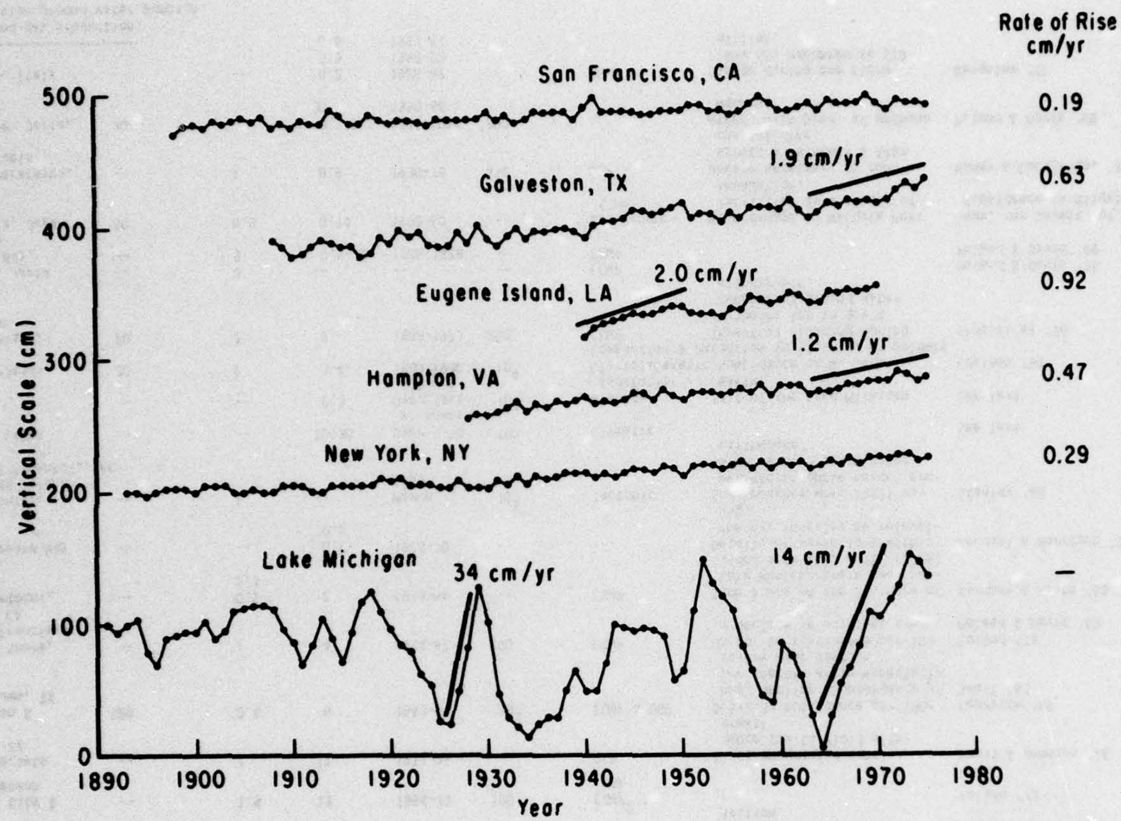

Fig. 1 Historic Changes in Water Level Elevation. Rates of relative rise averaged over the period of record shown, appear to the right. Rates for selected shorter periods are also indicated. Annual mean sea levels and lake level data are from National Ocean Survey NOAA.

Table 1. SELECTED SITES OF RECENT COASTAL SUBMERGENCE

LOCATION	SUBSIDENCE MEASUREMENTS Max. Rate Short Time (cm/yr)	Max. Cumulative (m)	Long Term Rate (cm/yr)	Period (yr)	AREA AFFECTED (km^2)	CAUSE	OTHER REMARKS	REFERENCES
Long Beach, CA	75	9	22	1926-67	50	OGP[1]	$100 million damage prior to control by water injection.	Allen & Mayuga '69 Mayuga & Allen '69
Texas City & Galveston	--	1.5	13	1964-73	100	EGWP[2] & OGP		Poland '73
San Jacinto Bay, TX	--	1	12	1917-25	--	OGP	First documented subsidence due to fluid withdrawal.	Pratt & Johnson '26
Houston & Baytown, TX	120	2.4	6	1943-64	10^3	EGWP & OGP	0.5-2.5m subsidence per 100m head decline. Submergence of low coastal areas especially severe near Baytown.	Gabrysch '69 Small '63
South Shore, San Francisco Bay, CA	--	1	4	1934-67	200	EGWP	Up to 10m subsidence per 100 m decline in adjacent areas.	Poland '73 Poland & Davis '69
New Orleans, LA	--	0.5 0.3	2	1938-64	--	EGWP	Some areas on the S. shore of Lake Pontchartrain have subsided more than a ft. (33cm)	Kazmann & Heath '68
Chesapeake Bay	--	--	0.1-0.5	1928-70	--	--	Details of variations within the bay revealed by releveling.	Holdahl & Morrison '74
Cook Inlet, Kodiak Island Kenai Peninsula, AK	--	1	--	March 1964	10^5	Tectonic	Some beaches were still experiencing above normal erosion rates 3 years after earthquake.	Stanley '68
Great Lakes	--	--	10-30	Over 3-10 yr spans	10^4	Climatic		See Text
	--	--	0.3	Over last 100 yrs	10^4	Glacio-isostatic	Tilt of the Lake Michigan basin.	See Text
Netherlands	30	2	3-4	1880-1930's	10^4	Glacioisostatic Compaction & Oxidation	Subsidence on N. Coast in vicinity of polders.	Edelman '54
Nobi Plain, Japan	20	2	2	1888-1973	250	EGWP	Threat of flooding during typhoons led to gov't control of ground water withdrawals.	Iida et al '76
Tokyo, Japan	--	4	--	--	--	EGWP		Poland & Davis '75
Osaka Bay, Japan	--	3	0.5-13	1885-1928	--	EGWP		Poland & Davis '69
Niigata, Japan	50	0.8	0.14	1900-60	--	Gas Production	Much damage to Niigata Port facilities as a result of inundation.	Comm. for Invest. of Earth Subsidence in Niigata '58 --
Lake Maracaibo, Venezuela	--	4	0.9	1930-75	450	OGP	Became necessary to construct & maintain a 44km coastal dike.	Nunez & Escojiido, '76
Po River Delta, Italy	30	--	0.1-0.3 30	1880-1950 1950-56	800		Assoc. with prod. of methane waters.	Poland & Davis '69
Venice, Italy	--	--	0.2 0.3 0.5	1926-42 1942-52 1953-61		EGWP	Damage during one storm (Nov 66) amounted to $70 million.	Berghinz '71

[1] Oil and gas production.
[2] Excessive ground water pumpage.

climatic and meterologic water level fluctuations. Selected coastal areas subject to recent submergence are listed in Table 1, along with descriptive data, and references. In the interest of guiding the engineer to additional sources of information, the original references are cited in the table even though some of the data were actually obtained from an excellent review by Poland and Davis (1969). Further reviews of subsidence case histories are provided by Poland (1973), and by the Proceedings of the First and Second International Symposiums on Lake Subsidence (IASH, Tokyo, 1969; IAHS, Anaheim, 1977).

3. Consequences.

Coastal submergence resulting from a variety of causes has thus been responsible for great damage in selected areas. The principal types of damage are: a) failures of structures due to ground motion, b) changes in the gradient of natural and man-made water transport systems due to tilt, c) increased flooding, and d) accelerated shore erosion.

a. Structural failures. In the case of earthquakes, ground-motion damage is familiar; but gradual land subsidence can also cause serious structural damage. In cases where the zone of vertical compaction is located at some significant depth below the surface, and there is significant tilt across the affected area, horizontal stresses become important. On the ground surface, horizontal strains develop in the central portion of the depression and extension strains develop along the periphery (Fig. 2).

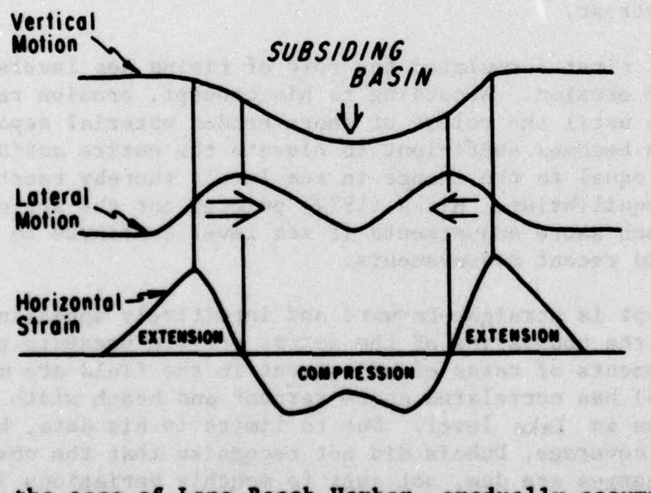

Fig. 2 Idealized Horizontal Strains Associated with Deep Compression and Subsidence (after Lee and Shen, 1969).

In the case of Long Beach Harbor, gradually accumulating horizontal stresses buckled railroad tracks and pipelines, damaged buildings and bridge supports, and sheared off hundreds of oil wells (Mayuga and Allen, 1969). Subsidence-induced horizontal stresses have also been implicated in dam failure. For more information on these aspects consult (Lee and Shen 1969, and Kapp 1977).

b. Changing gradients. Tilting of the ground surface can seriously affect the capacity of sewers and drains, and change the pattern of surface water run off. These problems are most serious in cities built on low lying coastal plains. In discussing subsidence in Houston, TX, Winslow and Wood (1959) suggest a beneficial effect: subsidence has deepened the Houston ship channel and thus reduced dredging requirements.

c. Increased flooding. In some areas where sea walls and levees have been constructed to prevent flooding, it has been necessary to progressively raise the height of the protective structures to counterbalance continued sinking of the coast (e.g., Lake Maracaibo, Long Beach, CA;and Tokyo). Tagami et al., (1969) discuss a procedure used to determine a desired or "maintained height", for sea walls in Japan considering astronomical and meteorological tides, storm waves, and rates of land subsidence.

d. Shore erosion. Due to the lengthy period between major geodetic relevelings, land subsidence has sometimes gone unrecognized for long periods, even in areas subject to anomalously high rates of subsidence. The first indications of broad subsidence have often been the tide level record, or direct evidence of the sea incroaching over unprotected,low-lying areas. The National Geodetic Survey is presently compiling a data base for vertical crustal movement in the US, which will make vertical velocity measurements readily available to engineers and scientists upon request (Holdahl and Morrison 1974). This effort will probably lead to the recognition of more widespread, subtle subsidence in the US. Even on coasts where barrier dunes prevent flooding, modest rates of subsidence may cause significant coastal erosion and long term shore retreat.

Bruun, (1962) first formulated the role of rising sea levels in accelerating shore erosion. According to his concept, erosion rates should remain high until the volume of shore eroded material deposited on the outer beach becomes sufficient to elevate the entire *active profile,* a height equal to the change in sea level; thereby reestablishing a profile of equilibrium. Hicks (1972) pointed out the serious consequences of such shore adjustments if sea level continues to rise at rates similar to recent measurements.

Bruun's concept is straight-forward and intuitively appealing. However, defining the boundaries of the *active profile* presents problems, and measurements of rates of adjustment in the field are meager. Dubois (1975, 1976) has correlated shore retreat and beach width to seasonal variations in lake level. Due to limits in his data, both in time and in areal coverage, Dubois did not recognize that the observed monthly profile changes are due, not just to monthly variations in littoral forces, but also to accumulated stresses induced by a 7-year rise in the mean water level, prior to his field study. More extensive measurements discussed later in this paper, show that the response of Lake Michigan shore profiles to these changes in mean water level, involved bathymetric adjustments across the entire nearshore zone out to depths of 9m. The outer bars are not relic as they appeared to Dubois (1977, p. 494) and the relationship of shore retreat to rising lake

level can not be predicted from either slope measurements or sediment budget calculations which are confined to only a small portion of the active profile.

The correlation between erosion and long term fluctuations in water level on the Great Lakes has been discussed by Berg (1965), Berg and Duane (1968), Saylor and Hands (1970) and Seibel (1972). Schwartz (1965, 1967, and 1968) used both laboratory and field data to demonstrate the Bruun concept on time scales varying from minutes to 10^4 years. Schofield (1967, 1975a, and 1975b) related beach progradation and spit building in New Zealand during the last 4,000 years to land emergence,and beach recession during the last 30 years to the effect of rising sea levels. The remainder of this report will review additional studies which further increase our understanding of the rates, and of the areal extent, of long term profile adjustments in response to coastal submergence.

RETREAT OF LAKE MICHIGAN IN RESPONSE TO SUBMERGENCE

1. Lake Michigan Water Levels.

As shown in Fig. 1, the annual mean elevation of Lake Michigan is not only subject to more extreme variations than is sea level, but also shows greater variance of the historic series is associated with cycles approximately 11 years in duration. During the rising phases of these *long term fluctuations* (1926-29, 1934-43, 1949-52, 1964-73) the mean lake level rose for several years at average rates of 34, 10, 22, and 14 cm/yr. These rates are comparable to high rates of submergence in areas of extreme coastal subsidence (table 1) and are appreciably greater than rates of submergence on most US shorelines. The response of the lake shore during prolonged increases in water level, gives direct insight into coastal changes that can be expected in response to rapid coastal subsidence. Combined with other field data, the lakeshore response can also serve as input to a model for estimating long term effects of more gradual sea level change on ocean shores.

2. Profile Adjustment to the Recent Rise in Lake Levels.

Response of the beach to the most recent episode of rising lake levels (1964-1973) was monitored at six stations in the vicinity of Pentwater Harbor about midway along the eastern shore of Lake Michigan. This study of profile changes provided an estimate of the increase in shoreline retreat due to increased lake levels, permitted the resolution of shore retreat into one component due to inundation and another due to erosion, and revealed simultaneous changes across the entire nearshore area (Hands, 1976). The dates of the four field seasons together with the changes in lake level between the field seasons (based on average daily means), and the mean monthly elevations during a six year period are given in Figure 3.

a. Shore. The net retreat of the shoreline over the study period is shown in Table 2 and Fig. 4A. In spite of slightly higher lake levels in the fall of 1969, the shoreline advanced between the spring and fall at two of the six profile stations (3 & 7) because

a small coastal bar merged with the shore, Over the long period, between spring of 1969 and 1971, a net retreat developed at all stations.

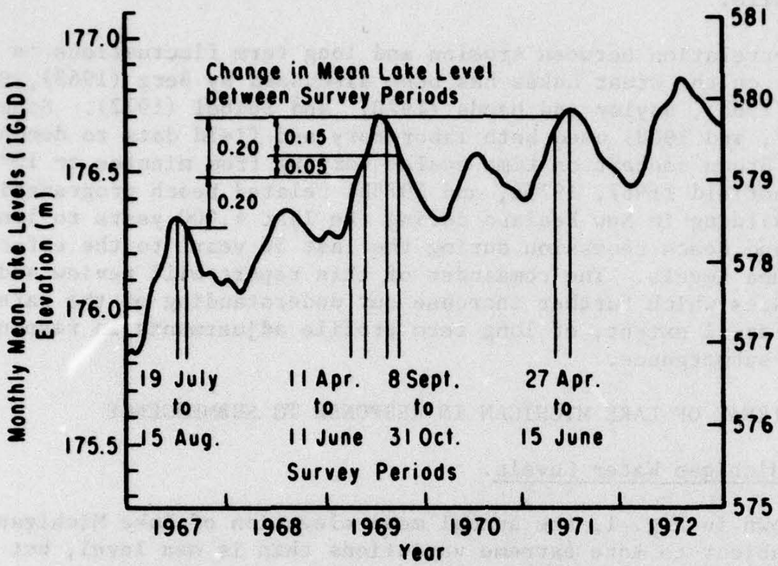

Fig. 3 Lake Michigan Hydrograph Showing Differences in Mean Lake Levels Between the Various Survey Periods, (from Hands, 1976).

The average retreat rate for the two year period was 4 m/yr, but there was still a considerable, random variation, among the different stations. Over the 45 month period (1967-1971) longshore variations in rate nearly vanished as all stations approached the average retreat rate of 4 m/yr, which illustrates the principle that the proper spacing of measurements needed to determine mean rates of retreat, decreases with time.

Table 2. Net Shoreline Retreat at Pentwater Michigan

Station Number	Spring to Fall 1969	Spring 1969 to 1971	1967 to 1971
3	-1.5[1]	1.5	13.4
4	1.5	12.0	16.7
5	2.5	10.7	14.6
6	3.3	7.5	15.2
7	-0.2[1]	5.8	16.9
8	2.0	12.5	11.0
Avg. retreat (m)	1.3	8.3	14.6
Coefficient of variation (m)	1.4	0.51	0.15
Avg. retreat rate (m/yr)	3.3	4.1	3.9

[1] negative retreat indicates the shore advanced lakeward.

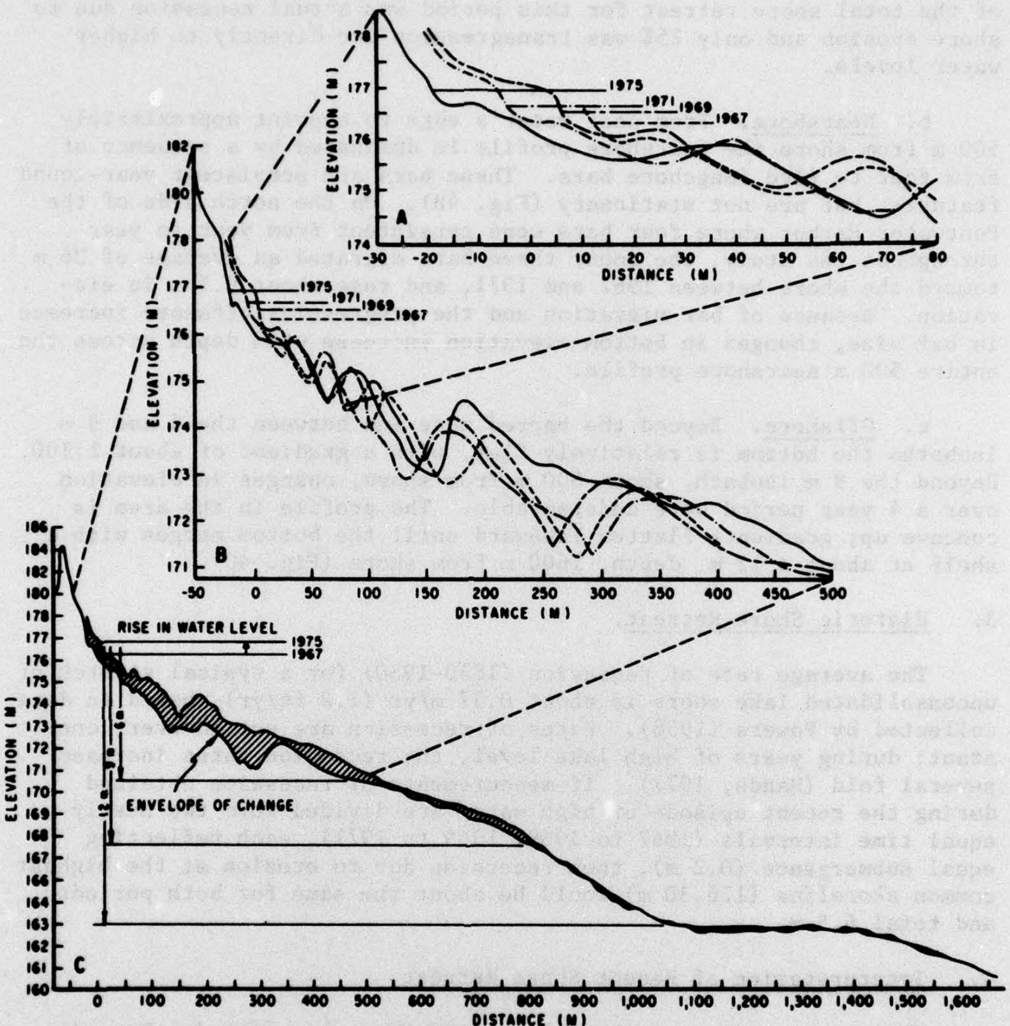

Fig. 4 Profile Adjustment to Rising Water Levels Over an 8 Year Period. Measured at station 4 near Pentwater on eastern shore of Lake Michigan.

The mean elevation of the lake surface rose 0.2 m between the 1969 and 1971 surveys. The resulting net shore retreat was 8 m. Recession measured at the 176.70 datum averaged 6 m, i.e., about 75% of the total shore retreat for this period was actual recession due to shore erosion and only 25% was transgression due directly to higher water levels.

b. Nearshore. From near water's edge to a point approximately 500 m from shore the nearshore profile is dominated by a sequence of from four to five longshore bars. These bars are persistent year-round features, but are not stationary (Fig. 4B). On the north side of the Pentwater Harbor where four bars were persistent from year to year throughout the study, the inner three bars migrated an average of 26 m toward the shore between 1967 and 1971, and rose about 0.5 m in elevation. Because of bar migration and the progressive offshore increase in bar size, changes in bottom elevation increase with depth across the entire 500 m nearshore profile.

c. Offshore. Beyond the barred zone and between the 6 and 9 m isobaths the bottom is relatively flat, with a gradient of about 1:100. Beyond the 9 m isobath, about 800 m from shore, changes in elevation over a 4 year period were undetectable. The profile in the area is concave up; gradients flatten lakeward until the bottom merges with a shelf at about a 12 m depth, 1600 m from shore (Fig. 4C).

3. Historic Shore Retreat.

The average rate of recession (1830-1950) for a typical stretch of unconsolidated lake shore is about 0.37 m/yr (1.2 ft/yr), based on data collected by Powers (1958). Rates of recession are not however, constant; during years of high lake level, the recession rates increase several fold (Hands, 1977). If measurements of recession obtained during the recent episode of high water are divided into two nearly equal time intervals (1967 to 1969, 1969 to 1971), each reflecting equal submergence (0.2 m), then recession due to erosion at the highest common *shoreline* (176.30 m) would be about the same for both periods and total 6.5 m.

4. Interpretation of Recent Shore Retreat.

The average net recession of the *176.30 m shoreline* is shown in Fig. 5 together with the simultaneous change in position of the bar crests and longshore troughs. Changes in elevation of crests, troughs, and *shoreline* were essentially equal (0.55, 0.47, and 0.51 m, respectively). Average horizontal changes were 25 m for the crests, 24 m for the troughs, but only 6.5 m for the 1967 *shoreline*. The much smaller landward migration of the shoreline was interpreted as indicating a lag in the response of the shoreface to submergence. To bring the profile in to equilibrium with the elevated lake level, it was felt that the upper beach would have to continue to recede even after lake levels stabilized.

Annual mean elevation of Lake Michigan reached a peak in 1973, 1.4 m above the annual mean elevation of 1964. During the next year some

monthly means were slightly higher, some slightly lower than the corresponding monthly means of 1973; on the whole the annual mean remained essentially unchanged. Over the next 2 years, (1975, 1976) mean water elevations fell slowly. Preliminary analysis of 1975 and 1976 profile data incidates that shore erosion rates did not abate during the 1971 to 1975 period even though the mean lake levels fell slightly. In 1976 retreat rates dropped at most, but not all stations. This tends to confirm the earlier prediction that erosion of the shoreface would lag several years behind lake level changes.

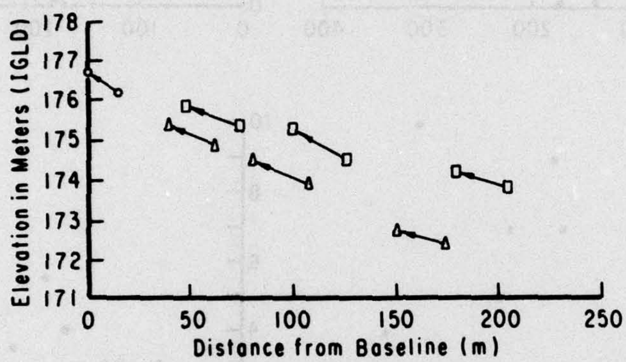

Fig. 5 Migration of Bars and Shoreline (1967 to1971). Migration of bar crests □, trough thalwegs Δ, and the shoreline o, from their mean positions in 1967 to their mean positions in 1971. Based on profile measurements at the three stations north of Pentwater Harbor (from Hands, 1977).

Assuming continued shore erosion would supply a volume of sediment sufficient to readjust the entire 500 m nearshore profile, the results of a crude sediment balance suggested that the final ratio of shore recession to submergence would be on the order of 60:1 (Hands, 1976). Recently collected survey data provide more extensive coverage both along shore and offshore, and thus may provide a basis for future refinement of the sediment budget approach and of the lag time between lake level change and complete profile response to attain equilibrium.

5. Interpretation of Historic Trends in Shore Retreat.

By selecting, from Powers' (1958) report, 94 stations initially surveyed between 1830 and 1838 and plotting historic shore retreat against station position projected on a mid-lake axis, regional trends were obtained (Fig. 6). An explanation for such trends was sought by examining alongshore variations in resistance of shore deposits to erosion, in offshore bathymetry, and in the degree of protection from winter waves afforded to various areas of the shore by pack ice. None of these variables showed any indication of regional trends.

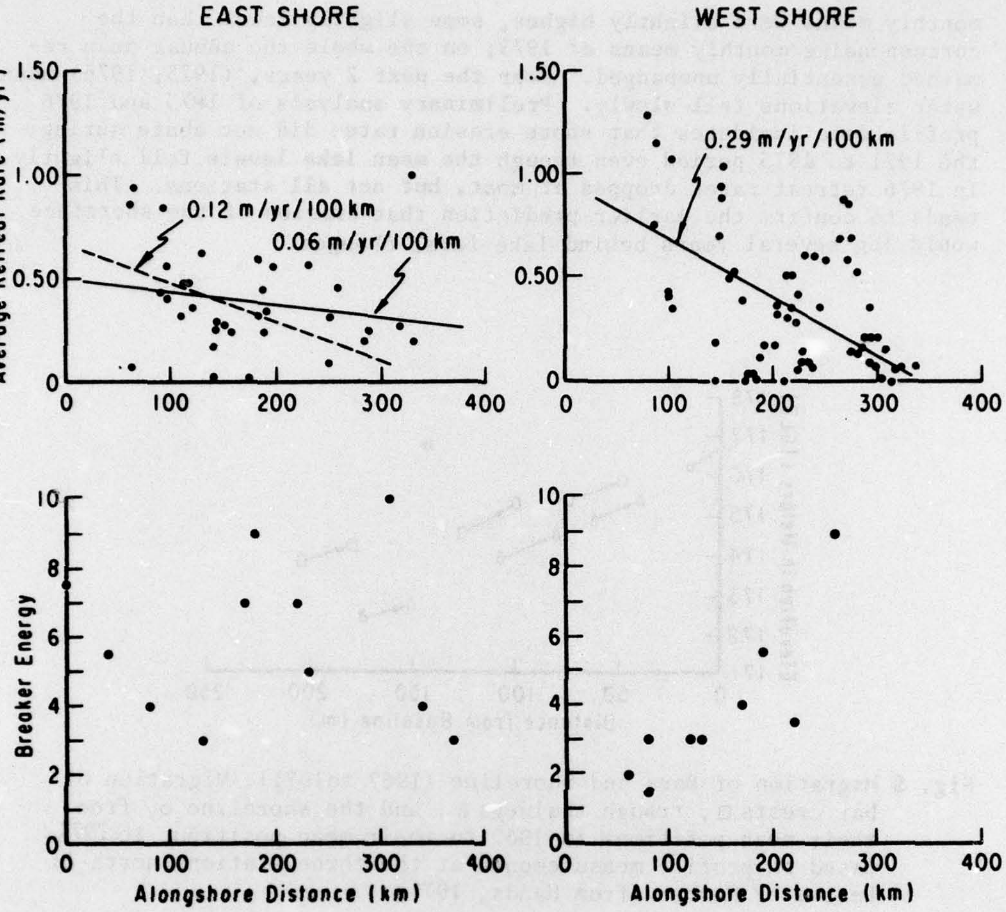

Fig. 6. Longshore Variations in Historic Retreat Rates (top) and Wave Energy in the Breaker Zone (bottom) on Lake Michigan. Abscissa values give positions of shore stations projected on a mid-lake axis, positive toward the north. Note the apparent decrease in rates of shore retreat toward the north on both eastern (top left) and western (top right) shores. Estimates of the rate of longshore change were obtained by least square regression. Solid and dashed lines (upper left) indicate the variability of the estimate, depending on whether the anomalously high value reported at 330 km on the east shore is retained or omitted in the analysis. In either case there is strong evidence for a regional decrease in historic recession rates. Contrast these trends in shore retreat (upper plots) with the lack cf any evidence that cumulative wave energy decreases northward (lower plots based on LEO, see text). In fact on the western shore, wave energy increases toward the north. Relative breaker energy was plotted on an arbitrary scale from zero to ten.

The possible effect of varying exposure to wave action was examined using observations from 20 Littoral Environmental Observation (LEO) stations that had reported daily surf data for a common 3 year period. As shown in the lower part of Fig. 6 breaker energy (arbitrary units) varies irregularly along the lake's eastern shore. On the west shore, the record indicates increasing wave energies toward the north. The occurrence of higher waves toward the north on the west shore was also evident from earlier visual wave observations by the Coast Guard (Liu and Housley, 1969). This apparent trend in wave energy is however, in the wrong direction to serve as a simple explanation for trends in recession rates. Thus longshore variations in wave exposure offer no explanation for observed trends in historic shore recession (Fig. 6).

By process of elimination, gradual submergence of the southern end of Lake Michigan appeared to be the principal cause for the regional trends in recession rates. Based on increasing differences in mean water level measured at various stations, Kite (1972) contoured the rate of vertical crustal motion throughout the Great Lakes area. Vertical crustal motion was mapped by Holdahl based on geodetic releveling (Meade, unpub). Estimates of the rates of recent tilt across the Lake Michigan basin from these two independent sources are in close agreement: .063 and .087 m per century per 100 km measured along the lake axis. Both the crustal motion studies (Fig. 7) and the record of historic shore retreat cover roughly the same period of time.

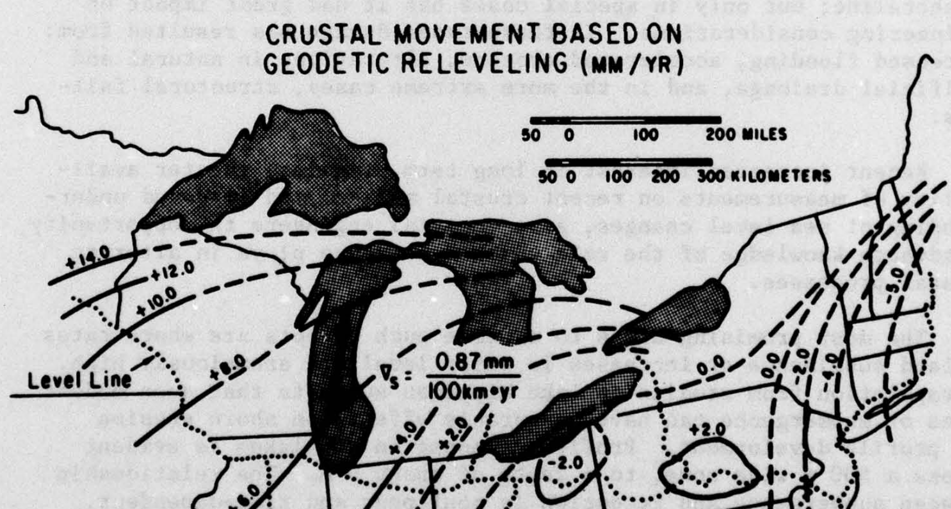

Fig. 7 Comparison of First Order Level Net of 1929 with First Order Releveling in 1955 Indicates Basin Tilt (from Meade, unpub). Survey path shown by dotted line. Gradient in rate of uplift (∇_s)was obtained by measurement along mid-take axis shown by arrow.

Given the uncertainties in rates of tilt and bluff recession, any possible relationship between submergence and retreat rates should be examined in the simpliest manner possible. A quantitative result was obtained by comparing their linear trends. The least square regression coefficient for the 94 shore measurements was 19 ± 10 ($X \pm 2S$) m per century per 100 km along the lake axis. Each centimeter of subsidence would thus be responsible for between one to four meters of increased recession if the trend in recession is to be attributed solely to submergence.

Based on this assumption the ratio of slow submergence to historic shore retreat would be between 1:100 and 1:400, as compared to a ratio of about 1:60 obtained from measurements over the recent 4 year period of increasing lake levels. Slow, long term profile adjustments may permit littoral forces to spread shore-eroded material over a more extensive area, and therefore, result in a greater shore loss than would result during a short period of equal but rapid subsidence. In agreement with the concept of sediment balance, the increase in recession per unit of subsidence is more pronounced on the relatively low western shore. For each unit of distance that high bluffs retreat, more sediment is supplied to build the outer profile than results from equal recession on low shores.

SUMMARY

Coastal subsidence can occur either suddenly or gradually. It results from a multitude of causes, some man-made, some natural. It is a condition that exists to some extent on almost all sections of the US shoreline; but only in special cases has it had great impact on engineering considerations. In these cases damage has resulted from: increased flooding, accelerated erosion, alterations in natural and artificial drainage, and in the more extreme cases, structural failures.

Recent increased interest in long term planning, greater availability of measurements on recent crustal motion, and improved understanding of sea level changes, give coastal engineers the opportunity to advance knowledge of the role which subsidence plays in altering coastal processes.

The most promising areas to observe such effects are where rates of land subsidence or increases in water level are anomalously high. Extrapolation from studies on Lake Michigan suggests that even modest rates of submergence can have measurable effects on shore erosion and profile development. Profile response on the lakes is evident across a 500 m wide zone, to a depth of about 9 m. The relationship between submergence and recession is nonlinear and time-dependent. Complete profile adjustment lags years behind changes in water level. Greater retreat is observed in areas where recession supplies a smaller volume of material per unit of retreat. This is in keeping with the sediment budget concept of profile response. The rates of shore retreat due to subsidence varied from 1 in sixty to 1 in several hundred. In coastal areas with similar geology, geomorphology, and wave exposure roughly similar responses may be expected. In areas having broad active profiles, low backshores, offshore or longshore sediment

sinks, as well as in areas where the eroding backshore contains a large percentage of material which would be unstable as a nearshore deposit, the ratio of retreat to submergence should be larger. Narrow active profiles, high backshore deposits, coarse grain sizes, and increased supplies of sediment from outside the control section, will all tend to diminish the ratio of shore retreat to submergence. Collection of additional data may make it feasible, to one day, derive relationships between subsidence and resulting shore retreat which may be valid for broad classes of coastal conditions.

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Submergence affects most U.S. shorelines, and has created serious problems in many localities by increasing flooding, accelerating erosion, altering surface drainage, and causing structural damage. This paper presents selected examples illustrating the problems engineers face in areas of coastal submergence and discusses in general how sea-level changes affect long-term shore processes.

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